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CHARM PHYSICS – LIKE BOTTICELLI IN THE SISTINE CHAPEL [1]

I. I. Bigi

Physics Dept., Univ. of Notre Dame du Lac, Notre Dame, IN 46556, U.S.A.

e-mail address: bigi@undhep.hep.nd.edu

Abstract

After sketching heavy quark expansions as applied to heavy flavour decays I emphasize the relevance of nonperturbative dynamics at the charm scale for exclusive $b \to c$ modes. I address the issue of quark-hadron duality for charm and discuss both the experimental and theoretical status of $D^0 - \bar{D}^0$ oscillations. Finally I argue that comprehensive CP studies of charm decays provide novel portals to New Physics and suggest benchmark figures for desirable sensitivities.

Contents

[1] Invited talk given at KAON 2001, the 3th International Conference on CP Violation, Pisa, Italy, June 12 - 17, 2001

1 Introduction

Since the title of my talk is admittedly far from illuminating, let me explain its meaning. There is an unimpeachable reason to visit the Sistine Chapel, namely to see Michelangelo's frescoes. For me they realize the power of beauty. Most of you who have been in the Sistine chapel will have forgotten – or maybe never have noticed in the first place – that halfway up the sidewalls there are wonderful frescoes by other famous masters, namely Botticelli, Perugino and others. They are not quite on the same unique level of Michelangelo's frescoes, yet had they been at almost any other place in the world, people would undertake pilgrimages to see just them!

Now I can state my analogy: I concede that the fascination of charm decays might not match that of beauty (or of strange) decays anymore than Botticelli can match the power of Michelangelo (or Rafaello)! Of course, Botticelli is still Botticelli, i.e. a first-rate artist, but what about charm? After all, the *weak* phenomenology that the *Standard Model* (SM) predicts for charm is on the dull side. I will argue that future charm studies can provide us with first rate lessons on fundamental dynamics taking my cue from the two items italized in the previous sentence:

- With the weak dynamics expected to be well known, detailed charm studies provide us with a test bed for theoretical QCD technologies.

- Since features specific to the SM make the weak phenomenology dull, charm transitions allow a novel access to the flavour problem with most – though not all – experimental conditions being a priori favourable!

Accordingly my talk will focus on two topics: (A) Heavy quark expansions and quark-hadron duality at the charm scale with a discussion of $D^0 - \bar{D}^0$ oscillations and (B) Charm's promise of revealing New Physics mainly through studies of CP violation.

2 QCD Technologies

While we have no solution of full QCD, we do have theoretical technologies inferred from QCD for special situations that allow us to deal with nonperturbative dynamics in an internally consistent way. Those are chiral perturbation theory for pion and kaon dynamics and heavy quark expansions (HQE). The latter apply to various aspects of the dynamics of beauty hadrons and possibly of charm hadrons as well. However since the charm quark mass exceeds ordinary hadronic scales by a moderate margin only, one can expect at best a semi-quantitative description there.

Simulating QCD on the lattice represents a technology of wide reach. In principle lattice QCD could work its way up to the charm scale from below. However the considerable advances achieved recently on the lattice with respect to heavy flavour physics were not based on such a 'brute-force' approach, but on a judicious use of $1/m_Q$ expansions [1].

Quark models are still very useful – if proper judgement is used. Subtle, yet relevant field theoretic features of QCD entering in the operator product expansion (OPE) like scale dependance are often not realized in quark models, unlike in HQE.

2.1 Heavy Quark Expansions

In HQE one describes an observable γ for a hadron H_Q – be it a total rate or a distribution – through an expansion in inverse powers of the heavy *quark* mass obtained through an operator product expansion (OPE) [2] constructed at small Euclidean space-time intervals m_Q:

$$\gamma(E) = \sum_i c_i(\alpha_S, E)(\Lambda_i/m_Q)^i \; ; \tag{1}$$

E denotes the relevant energy scale. Dispersion relations that have to be exact as long as QCD does not generate unphysical singularities in the complex plane connect the coefficients of the OPE with moments of the observable distributions in Minkowski space. This is expressed through sum rules [3, 4], which can generically be expressed by

$$\int dE w(E)\gamma(E)|_{hadrons} = \int dE w(E)\gamma(E)|_{quarks} \tag{2}$$

stating that the integral of such observable γ weighted by some function $w(E)$ has to be equal when expressed in terms of hadronic or quark degrees of freedom. This is referred to as (global) quark-hadron duality or duality for short.

Such methods are applied to *in*clusive transitions – lifetimes, semileptonic branching ratios, lepton spectra etc. – and *ex*clusive observables like semileptonic form factors.

Quark models are still the best we have for treating nonleptonic two-body modes of charm mesons. I understand there are several reasons why the recently suggested methods for $B \to M_1 M_2$ [5] are hard to justify for charm decays; one is that nonleading corrections $\sim \mathcal{O}(1/m_Q)$ cannot be treated (yet). Nevertheless one should try them there anyway!

2.2 Applications: Lifetimes

The HQE yields a more successful description of the pattern in the weak lifetimes of charm hadrons than could a priori be expected, in particular since those lifetimes differ by more than an order of magnitude between $\tau(D^+)$ being the longest and $\tau(\Omega_c)$ the shortest. Since no new data on lifetimes were presented at this meeting, let me just make a few comments here; my more detailed evaluation can be found in [6]:

• The HQE provides an after-the-fact rationale for most phenomenological concepts like Pauli Interference, Weak Annihilation (WA) etc. as $\mathcal{O}(1/m_c^3)$ effects.

• It makes more definitive statements about the weight of those concepts. For example, WA has to be a *non*leading effect in *meson* decays, although it could still be quite significant.

• An important quantity is the ratio $\tau(D_s)/\tau(D^0)$. Its first measurement by E 687, the precursor of FOCUS, gave the first experimental confirmation that WA is indeed *not* a *leading* mechanism for generating the D^+-D^0 lifetime difference. It also provided clear evidence that the D_s lifetime exceeds that of D^0 by a moderate amount. A new round of very high statistics experiments has begun. The world average from last summer reads [7]

$$\tau(D_s)/\tau(D^0) = 1.18 \pm 0.02 \quad (3)$$

rather than the previous world average of 1.125 ± 0.042. A new SELEX number is a bit lower: $\tau(D_s)/\tau(D^0) = 1.145 \pm 0.049$; new measurements from

FOCUS and the beauty factories will be added soon. Anticipating the new world average to settle in around 1.2, it confirms that WA is not the leading source of lifetimes differences among charm mesons; at the same time it shows WA to be still significant at the about 20 % level, as expected [8]. The apparent fact that due to WA 10 - 20 % of *all* D_s decays are interfered away should leave some clear footprints in certain classes of exclusive channels. This could be studied, e.g., by comparing Dalitz plots of Cabibbo suppressed D^0 and D^+ modes with Cabibbo allowed D_s channels.

• In contrast to quark model treatments the HQE allow to understand the *absolute* D^0 and D^+ semileptonic branching ratios as due to $1/m_c^2$ effects.

• Predictions on baryon lifetimes involve quark model estimates of various expectation values and thus are subject to large theoretical uncertainties.

• We need $\sim$ 10 % measurements of both Ξ_c^+ and Ξ_c^0 lifetimes. They could easily reveal systematic problems in the HQE predictions and have a significant impact on our understanding of *beauty* baryon lifetimes.

• The *ratios* of semileptonic branching ratios for *baryons* do *not* reflect their lifetime ratios!

2.3 Theoretical uncertainties

Since no clear evidence for New Physics has been found yet in charm transitions (see the discussion below), it would be tempting to declare victory and move on to presumably greener pastures. I want to list three reasons why charm physics still merits our dedicated attention:

- It can still provide us with new insights into the inner workings of QCD.
- It allows us to calibrate the theoretical tools we are using in extracting CKM parameters in B decays: measuring both decay constants f_D and f_{D_s} accurately and comparing them with unquenched lattice results will enable us to predict f_B with more confidence; likewise a precise extraction of the form factors in $D \to l\nu K/K^*/\pi/\rho$ and their q^2 dependance will be of direct as well as indirect help in extracting $|V(ub)|$ from $B \to l\nu\rho/\pi$.
- The third motivation is not obvious: the relevant scale for the nonperturbative dynamics in *exclusive* $b \to c$ modes is given by the charm

mass. In particular in $B \to l\nu D^*$ the most relevant preasymptotic effects are given by the expansion in $1/m_c$ rather than $1/m_b$. Also the D^* width has an impact on the accuracy with which the formfactor for $B \to D^*$ even at zero recoil can be predicted. A comprehensive analysis of charm decays can shed light on such dynamics.

The central issue here is that of *theoretical uncertainties*. They are fed from some obvious sources – namely numerical uncertainties in input parameters like α_S – and not so straightforward ones reflecting more systematic uncertainties. Limitations to duality belong to the latter [9, 4].

Duality is a concept dating back to the early days of quark models. It is, however, rarely appreciated that over the last several years it has become a fairly precise concept in heavy flavour decays rather than the qualitative one it used to be; it also has to be viewed in the context of the paradigm that QCD is the theory of strong interactions. The corrollary of the latter is the statement that even hadronic observables can be evaluated exactly on the quark-gluon level *provided* all possible corrections to the quark-parton result are properly accounted for. Duality violations are thus due to corrections that could not be included due to a limitation in the *algorithm* employed.

The OPE has intrinsic limitations: when constructed in Euclidean space it has no sensitivity to terms of the type, say, $\exp\{-m_Q/\Lambda\}$. Such innocuous contributions turn into 'oscillating' terms $\sim \sin(m_Q/\Lambda)$ upon continuation to Minkowski space. Therefore the OPE will in general not yield correct predictions *point for point* in m_Q (or E etc.): some averaging or 'smearing' in that variable will be required; i.e., *local* duality will in general not hold. Furthermore the expansion even for Euclidean quantities is only asymptotic in $1/m_c$ and thus has irreducible errors even in principle.

In summary: charm studies can serve as a microscope for duality . *At best* we will encounter sizeable uncertainties; *at worst* we might be forced to conclude that duality is not operative yet at the charm scale.

2.4 A case study: $D^0 - \bar{D}^0$ oscillations

Oscillations are described by the normalized mass and width differences: $x_D \equiv \frac{\Delta M_D}{\Gamma_D}$, $y_D \equiv \frac{\Delta\Gamma}{2\Gamma_D}$. The experimental landscape is summarized by [10]:

$$x_D \leq 0.03 \tag{4}$$

$$y_D = \begin{cases} (0.8 \pm 2.9 \pm 1.0)\% \;\; \text{E791} \\ (3.42 \pm 1.39 \pm 0.74)\% \;\; \text{FOCUS} \\ (1.16^{+1.67}_{-1.65})\% \;\; \text{BELLE} \\ (-1.1 \pm 2.5 \pm 1.4)\% \;\; \text{CLEO} \end{cases} \tag{5}$$

$$y'_D = (-2.5^{+1.4}_{-1.6} \pm 0.3)\% \;\; \text{CLEO} \; . \tag{6}$$

y'_D is extracted from fitting a general lifetime evolution to $D^0(t) \to K^+\pi^-$ and depends on the strong rescattering phase δ between $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$: $y'_D = -x_D \mathrm{sin}\delta + y_D \mathrm{cos}\delta$. Obviously all measurements are still consistent with zero. Yet to judge how significant that statement is, we have to examine what the SM expectations are.

With $D^0 \to f \to \bar D^0$ transition amplitudes being proportional to $\mathrm{sin}\theta_C^2$ one has $x_D, y_D \leq 0.05$; furthermore in the limit of $SU(3)_{Fl}$ symmetry those amplitudes have to vanish. However a priori one cannot count on that being a very strong suppression for the real world; thus $x_D, \; y_D \sim \mathcal{O}(0.01)$ represents a conservative SM bound. On general grounds I find it unlikely – though mathematically possible – that New Physics could overcome the Cabibbo bound significantly. Comparing this general bound on the oscillation variables to the data listed in Eq.(5), I conclude the hunt for New Physics realistically has only just begun!

One can give a more sophisticated SM estimate for $x_D, \; y_D$. There exists an extensive literature on it; however some relevant features were missed for a long time. Quark box diagrams yield tiny contributions only: $x_D(\mathrm{box}) \sim$ few $\times 10^{-5}$. Various schemes are then invoked to describe selected hadronic intermediate states to guestimate the impact of long distance dynamics: $x_D(LD), \; y_D(LD) \sim 10^{-4} - 10^{-3}$. Recently a new analysis [11] has been given based on an OPE providing a systematic treatment in powers of $1/m_c$, the GIM factors m_s and the CKM parameters. It finds that the GIM suppression by a factor of $(m_s/m_c)^4$, which is behind the result stated on $x_D(\mathrm{box})$ is *untypically severe* [12]. There are contributions with gentle GIM factors proportional to m_s^2/μ_{had}^2 or even m_s/μ_{had}. They are due to higher-dimensional operators and thus accompanied by higher powers of $1/m_c$. Since those are not greatly suppressed, contributions of formally higher order in $1/m_c$ can become numerically leading if they are of lower order in m_s. These terms are actually due to condensate terms in the OPE, namely $\langle 0|\bar q q|0\rangle$ etc. On the *conceptual* side we have achieved significant progress: it is again the OPE that allows to incorporate nonperturbative dynamics from the start in

a self-consistent way. *Numerically* there is no decisive change, although the numbers are somewhat larger with a better appreciation of the uncertainties:

$$x_D(SM)|_{OPE},\ y_D(SM)|_{OPE} \sim \mathcal{O}(10^{-3})\ . \tag{7}$$

Yet despite the similarities in numbers for x_D and y_D the dynamics driving these two $\Delta C = 2$ observables are quite different:

- Δm_D being generated by contributions from virtual states is sensitive to New Physics which could raise it to the percent level. At the same time it necessarily involves an integral over energies thus making it rather robust against violations of local duality.

- $\Delta\Gamma_D$ being driven by on-shell transitions can hardly be sensitive to New Physics. At the same time, however, it is very vulnerable to violations of local duality: a nearby narrow resonance could easily wreck any GIM cancellation and raise the value of $\Delta\Gamma_D$ by an order of magnitude!

If data revealed $y_D \ll x_D \sim 1\%$ we would have a strong case to infer the intervention of New Physics. If on the other hand $y_D \sim 1\%$ – as hinted at by the FOCUS data – then two scenarios could arise: if $x_D \leq$ few $\times\, 10^{-3}$ were found, one would infer that the $1/m_c$ expansion within the SM yields a correct semiquantitative result while blaming the "large" value for y_D on a sizeable and not totally surprising violation of duality. If, however, $x_D \sim 0.01$ would emerge, we would face a theoretical conundrum: an interpretation ascribing this to New Physics would hardly be convincing since $x_D \sim y_D$. To base a case for New Physics solely on the observation of $D^0 - \bar{D}^0$ oscillations is thus of uncertain value, unless x_D is found to exceed y_D significantly!

3 CP violation in charm decays

Most of us view the SM as incomplete, and our efforts are focussed on uncovering New Physics. Charm decays have a good potential to reveal interventions of New Physics that might not be manifest in beauty decays [13]. For charm quarks are the only up-type quark allowing a full range of indirect searches for New Physics. While $D^0 - \bar{D}^0$ oscillations are slow, $T^0 - \bar{T}^0$ oscillations cannot occur at all, nor can CP violation there, since top quarks decay before they can hadronize [14]. Direct CP violation can emerge in

channel	World Average '00	CLEO '01
$D^0 \to K^+K^-$	$(0.5 \pm 1.6)\%$	$(0.1 \pm 2.2 \pm 0.8)\%$
$D^0 \to \pi^+\pi^-$	$(2.2 \pm 2.6)\%$	$(2.0 \pm 3.2 \pm 0.8)\%$
$D^\pm \to K^\pm K^-\pi^+$	$(0.2 \pm 1.1)\%$	
$D^0 \to K_S\pi^0$		$(0.1 \pm 1.3)\%$
$D^0 \to \pi^0\pi^0$		$(0.1 \pm 4.8)\%$

Table 1: Data on direct CP asymmetries in D decays

exclusive modes that command decent branching ratios for charm, but are really tiny for top with little coherence left. Finally charm decays proceed in an environment populated with many resonances which induce final state interactions (FSI) of great vibrancy. While this feature complicates the interpretations of a signal (or lack thereof) in terms of microscopic quantities, it is optimal for getting an observable signal. In that sense it should be viewed as a virtue rather than a vice.

Charm hadrons provide several practical advantages: their production rates are relatively large; they possess long lifetimes and $D^* \to D\pi$ decays provide as good a flavour tag as one can have. Charm transitions should thus be viewed as a *unique* portal for studying the *flavour* sector.

The most promising probe in such an enterprise is a comprehensive search for CP violation. The data are summarized in Table 1 [15, 16]. All numbers are still consistent with zero – on the level of a few percent. This represents an impressive increase in experimental sensitivity. Yet at the same time I consider it unlikely (though not inconceivable) that New Physics could induce CP asymmetries of 10 percent or more. Therefore the search for CP violation in charm transitions *only now* has entered a phase with real promise.

3.1 CP Violation – Expectations

(i) Direct CP Violation in Partial Widths

For an asymmetry to become observable between CP conjugate partial widths, one needs two coherent amplitudes with a relative *weak* phase and a nontrivial strong phase shift.

In Cabibbo favoured as well as in doubly Cabibbo suppressed channels those requirements can be met with New Physics only. There is one exception

to this general statement [17]: the transition $D^\pm \to K_S\pi^\pm$ reflects the interference between $D^+ \to \bar{K}^0\pi^+$ and $D^+ \to K^0\pi^+$ which are Cabibbo favoured and doubly Cabibbo suppressed, respectively. Furthermore in all likelihood those two amplitudes will exhibit different phase shifts since they differ in their isospin content. The known CP impurity in the K_S state induces a difference *without any theory uncertainty*:

$$\frac{\Gamma(D^+ \to K_S\pi^+) - \Gamma(D^- \to K_S\pi^-)}{\Gamma(D^+ \to K_S\pi^+) + \Gamma(D^- \to K_S\pi^-)} = -2\mathrm{Re}\epsilon_K \simeq -3.3 \cdot 10^{-3} \qquad (8)$$

In that case the same asymmetry both in magnitude as well as sign arises for the experimentally much more challenging final states $K_L\pi^\pm$. If on the other hand New Physics is present in $\Delta C = 1$ dynamics – most likely in the doubly Cabibbo suppressed transition – then both the sign and the size of an asymmetry can be different from the number in Eq.(8), and by itself it would make a contribution of the *opposite* sign to the asymmetry in $D^+ \to K_L\pi^+$ vs. $D^- \to K_L\pi^-$. An explicit model by D'Ambrosio and Gao [18] shows that a CP asymmetry $\sim \mathcal{O}(1\%)$ could indeed be induced by New Physics through the doubly Cabibbo suppressed amplitude that would have escaped detection so far; it would also affect Δm_D only insignificantly!

Searching for *direct* CP violation in Cabibbo suppressed D decays as a sign for New Physics would represent a very complex challenge: within the KM description one expects to find asymmetries of order 0.1 % [19, 20]; yet it would be hard to conclusively rule out some more or less accidental enhancement due to a resonance etc. raising an asymmetry to the 1% level. Observing a CP asymmetry in charm decays would certainly be a *first rate discovery irrespective of its theoretical interpretation*. Yet to make a case that a signal in a singly Cabibbo suppressed mode reveals New Physics is iffy. One has to analyze at least several channels with comparable sensitivity to acquire a measure of confidence in one's interpretation.

(ii) Direct CP Violation in Final State Distributions

For channels with two pseudoscalar mesons or a pseudoscalar and a vector meson a CP asymmetry can manifest itself only in a difference between conjugate partial widths. If, however, the final state is more complex – being made up by three pseudoscalar or two vector mesons etc. – then it contains more dynamical information than expressed by its partial width, and CP violation can emerge also through asymmetries in final state distributions. One general comment still applies: since also such CP asymmetries require

the interference of two weak amplitudes, within the SM they can occur in Cabibbo suppressed modes only.

In the simplest such scenario one compares CP conjugate *Dalitz plots*. It is quite possible that different regions of a Dalitz plot exhibit CP asymmetries of varying signs that largely cancel each other when one integrates over the whole phase space. I.e., subdomains of the Dalitz plot could contain considerably larger CP asymmetries than the integrated partial width. Once a Dalitz plot is fully understood with all its contributions, one has a powerful new probe. This is not an easy goal to achieve, though, in particular when looking for effects that presumably are not large. It might be more promising as a practical matter to start out with a more euristic approach. I.e., one can start a search for CP asymmetries by just looking at conjugate Dalitz plots. One simple strategy would be to focus on an area with a resonance band and analyze the density in stripes *across* the resonance as to whether there is a difference in CP conjugate plots.

For more complex final states containing four pseudoscalar mesons etc. other probes have to be employed. Consider, e.g., $D^0 \to K^+K^-\pi^+\pi^-$, where one can form a T-odd correlation with the momenta: $C_T \equiv \langle \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) \rangle$. Under time reversal T one has $C_T \to -C_T$ hence the name 'T-odd'. Yet $C_T \neq 0$ does not necessarily establish T violation. Since time reversal is implemented by an *anti*unitary operator, $C_T \neq 0$ can be induced by FSI [24]. While in contrast to the situation with partial width differences FSI are not required to produce an effect, they can act as an 'imposter' here, i.e. induce a T-odd correlation with T-invariant dynamics. This ambiguity can unequivoally be resolved by measuring $\bar{C}_T \equiv \langle \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}) \rangle$ in $\bar{D}^0 \to K^+K^-\pi^+\pi^-$; finding $C_T \neq -\bar{C}_T$ establishes CP violation without further ado.

Decays of *polarized* charm baryons provide us with a similar class of observables; e.g., in $\Lambda_c \Uparrow \to p\pi^+\pi^-$, one can analyse the T-odd correlation $\langle \vec{\sigma}_{\Lambda_c} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) \rangle$ [21].

(iii) CP violation involving $D^0 - \bar{D}^0$ oscillations

The interpretation is much clearer for a CP asymmetry involving oscillations, where one compares the time evolution of transitions like $D^0(t) \to K_S\phi$, K^+K^-, $\pi^+\pi^-$ [22] and/or $D^0(t) \to K^+\pi^-$ [23] with their CP conjugate channels. A difference for a final state f would depend on the product

$$\sin(\Delta m_D t) \cdot \mathrm{Im}\frac{q}{p}[T(\bar{D} \to f)/T(D \to \bar{f})] \ . \tag{9}$$

With both factors being $\sim \mathcal{O}(10^{-3})$ in the SM one predicts a practically zero asymmetry $\leq 10^{-5}$. Yet New Physics could generate considerably larger values, namely $x_D \sim \mathcal{O}(0.01)$, $\mathrm{Im}\frac{q}{p}[T(\bar{D} \to f)/T(D \to \bar{f})] \sim \mathcal{O}(0.1)$ leading to an asymmetry of $\mathcal{O}(10^{-3})$. One should note that the oscillation dependant term is linear in the small quantity x_D (and in t) – $\sin\Delta m_D t \simeq x_D t/\tau_D$ – in contrast to r_D which is quadratic: $r_D \equiv \frac{D^0 \to l^- X}{D^0 \to l^+ X} \simeq \frac{x_D^2 + y_D^2}{2}$. It would be very hard to see $r_D = 10^{-4}$ in CP insensitive rates. It could well happen that $D^0 - \bar{D}^0$ oscillations are first discovered in such CP asymmetries!

4 Summary and Outlook

We have learnt many important lessons from charm studies. Yet even so, they do not represent a closed chapter. On one hand charm physics can teach us many more important lessons about QCD and its nonperturbative dynamics beyond calibration work needed for a better analysis of beauty decays. On the other it provides a unique portal to New Physics through up-type quark dynamics. In this latter quest only now have we begun to enter promising territory, namely gaining sensitivity for x_D and y_D values of order percent and likewise for CP asymmetries.

Without a specific theory of New Physics one has to strike a balance between the requirements of feasibility and the demands of making a sufficiently large step beyond what is known when advocating benchmark numbers for the experimental sensitivity. In that spirit I suggest the following numbers:

1. Probe $D^0 - \bar{D}^0$ oscillations down to x_D, $y_D \sim \mathcal{O}(10^{-3}) \hat{=} r_D \leq \mathcal{O}(10^{-5})$.

2. Search for *time dependant* CP asymmetries in $D^0(t) \to K^+K^-$, $\pi^+\pi^-$, $K_S\phi$ down to the 10^{-4} level and in the doubly Cabibbo suppressed mode $D^0(t) \to K^+\pi^-$ to the 10^{-3} level.

3. Look for asymmetries in the partial widths for $D^\pm \to K_{S[L]}\pi^\pm$ down to 10^{-3} and likewise in a *host* of singly Cabibbo suppressede modes.

4. Analyze Dalitz plots and T-odd correlations etc. with a sensitivity down to $\mathcal{O}(10^{-3})$.

Huge amounts of new information on charm dynamics will become available due to data already taken by FOCUS and SELEX and being taken at the B

factories; there is activity to be hoped for at Compass, BTeV and LHC-B. And finally there are the activities that could be pursued at a tau-charm factory at Cornell. We can be sure to learn many relevant lessons from such studies – and there may be surprises when we least expect it.

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References

[1] S. Hashimoto & A. Kronfeld, in: Proc. of BCP4, Ise, Japan, Feb. 2001.

[2] I.I. Bigi, M.Shifman, N. Uraltsev, *Annu. Rev. Nucl. Part. Sci.* **47** (1997) 591, with references to earlier work.

[3] I.I. Bigi *et al.*, *Phys. Rev.* **D 52** (1995) 196.

[4] I.I. Bigi, N. Uraltsev, preprint hep-ph/0106346.

[5] M. Beneke, these Proc.

[6] I.I. Bigi, in: Proc. of BCP3, H.-Y. Cheng, W.-S. Hou (eds.), World Scientific, 2000, with references to earlier work.

[7] A. Golutvin, in: Proc. of ICHEP 2000, C.S. Lim, T. Yamanaka (eds.), World Scientific, 2001.

[8] I.I. Bigi, N. Uraltsev, *Z. Phys.* **C62** (1994) 623.

[9] M. Shifman, in: B. Joffe Festschrift *At the Frontier of Particle Physics*, M. Shifman (ed.), World Scientific, Singapore, 2001.

[10] C. Riccardi, these Proc.; V. Savinov, these Proc.

[11] I.I. Bigi, N. Uraltsev, *Nucl. Phys.* **B592**(2001) 92.

[12] This has been noted before by H. Georgi, *Phys. Lett.* **B297** (1992) 353.

[13] I.I. Bigi, in: Proc. of 'Heavy Quarks at Fixed Target 2000', I. Bediaga, J. Miranda, A. Reis (eds.), Frascati Physics Series, Vol. XX.

[14] I. Bigi *et al.*, *Phys. Lett.* **B 181** (1986) 157.

[15] D. Pedrini, in: Proc. of 'Heavy Quarks at Fixed Target 2000', I. Bediaga, J. Miranda, A. Reis (eds.), Frascati Physics Series, Vol. XX.

[16] A. Smith, in: Proc. of BCP4, Ise, Japan, Feb. 19 - 23, 2001.

[17] I. Bigi, H. Yamamoto, *Phys. Lett.* **B 349** (1995) 363.

[18] G. D'Ambrosio, D.-N. Gao, hep-ph/0105078.

[19] I.I. Bigi, in: SLAC-Report-343, June 1989.

[20] F. Buccella *et al.*, *Phys. Rev.* **D51** (1995) 3478.

[21] D. Benson, I.I. Bigi, in preparation.

[22] I.I. Bigi, A.I. Sanda, *Phys. Lett.* **B171** (1986) 320.

[23] I.I. Bigi, in: Proc. of the XXIII ICHEP, Berkeley, 1986, S. Loken (ed.), World Scientific; G. Blaylock, A. Seiden, Y. Nir, *Phys. Lett.* **B355** (1995) 555.

[24] See, e.g.: I.I. Bigi, A.I. Sanda,'CP Violation', Cambridge University Press 2000.